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PROGRAMMABLE AUTOMATION: THE FUTURE OF COMPUTERS

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13 ABSTRACT

This report is the first in a series of Information Sciences Institute Research Reports from a study currently in progress on advanced, computer-based automation of discrete product manufacture. The goals of this study are to: (1) evaluate the technological feasibility of significant advancements in computer-based automation of discrete product manufacture; (2) evaluate the economic impact on DoD, the military, and the U.S. economy derived from implementation of those advancements; (3) define the development program required to achieve those advancements, areas to be addressed and resources required; (4) perform R&D on innovative solutions for some components of the development program for Department of Defense consideration. This work is supported by the Advanced Research Projects Agency (ARPA) under Contract DAHC 15-72-C-0308.

This first report provides an overview of the concept of programmable automation. It emphasizes the importance of batch production techniques in the manufacture of DoD end-use items, and describes the importance of flexible, computer control of resources in such an environment. The components of a development program leading to significant productivity increases through computer based manufacturing systems are described. This article was written for publication in Datamation Magazine. (The article appeared in the December, 1972 issue.)

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PREFACE

This report is the first in a series of Information Sciences Institute Research Reports on Programmable Automation. This series will present research results from a study currently in progress on advanced, computer-based automation of discrete product manufacture. The goals of this study are to: (1) evaluate the technological feasibility of significant advancements in computer-based automation of discrete product manufacture; (2) evaluate the economic impact on DOD, the military, and the U.S. economy derived from implementation of those advancements; (3) define the development program required to achieve those advancements, areas to be addressed and resources required; (4) perform R&D on innovative solutions for some components of the development program for Department of Defense consideration. This work is supported by the Advanced Research Projects Agency (ARPA) under Contract DAHC 15-72-C-0308.

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PROGRAMMABLE AUTOMATION: THE FUTURE OF COMPUTERS IN MANUFACTURING

Robert H. Anderson

Probably the most explosive growth area for the application of information sciences during the next decade is in computer-based automation of the manufacturing process. All aspects of manufacture -- design, prototyping, production engineering, part forming, assembly, inspection, material transfer and storage -- will increasingly become directly controlled by computers. Furthermore, computer control will bring a new flexibility to automation; the machines that perform manufacturing operations will be programmable, allowing one machine to perform a variety of manufacturing steps. The capability, combined with complete computer-based scheduling and allocation of resources, will result in a major increase in manufacturing productivity, especially in the important area of batch production and job shop operations. In addition, most of the dull and demeaning jobs within a manufacturing facility will be replaced by more interesting and challenging tasks such as programming and system maintenance.

The purpose of this article is to describe the coming role of computers in manufacturing, the benefits to be expected from their use, and the development program needed to achieve those benefits.

First, it is important to distinguish among the various activities that are called "manufacturing."

Three Types of Manufacturing

Products (and their subcomponents) are manufactured by three different methods: process industries; mass production; and batch production.

Process industries create products by control of a continuous process; oil refineries and modern glass and steel production are conspicuous examples. Computer-based automation of process control in these facilities is highly advanced. Due to the continuous nature of the process, its manipulation requires only control of rather simple mechanical devices, such as valves, within a highly rigid system, based on sensor feedback requiring modest bandwidth and computation. Computers are clearly suited to the control of routine production, with humans performing supervision (requiring more complex pattern recognition) and maintenance (requiring more complex manipulation of objects). I will not consider manufacture by process industries further in this article.

Mass production of discrete objects on an assembly line is a second type of manufacturing process. The classic example is automobile production, with production rates exceeding 100 units/hour. Much higher rates are achieved for simpler objects, of course. There is a linear flow of in-process materials and subassemblies between work stations at which manufacturing steps are performed, usually by "hard" automation specially designed for the task. If all the products being mass-produced by an assembly line were identical, the impact of computers on the control of the production process would be minimal, for several reasons: little flexibility is required in the production machinery, therefore the control of that machinery is not complex; special-purpose "hard-wired" machines and control logic can outperform more general-purpose equipment, since they can take advantage of opportunities for parallelism and simultaneity (e.g., concurrent boring of eight cylinders in a V-8 engine block), and the cost of special-purpose equipment can be completely amortized over a long production run. But automobiles, for example, are not produced identically; they are custom-made to a considerable extent, so flexibility is needed -- ergo programmable Unimate industrial robots performing spot-welding in the General Motors Vega production plant -- and computer control of in-process inventories becomes required. However, the bulk of U.S. discrete product manufacturing is not produced by mass production, but rather by batch production techniques.

Batch production uses manufacturing facilities in a flexible manner. The facilities are configured to produce a particular product; that product is manufactured in a lot size varying from 2 or 3 to thousands; then the facilities are reconfigured to produce a different product. The reconfiguration may be modest, such as mounting a new tape and work-holding fixture on a numerically controlled machine tool, or it may be more extensive, requiring mechanical adjustments involving wrenches or cams, or a different set of procedures used by people in the operation of general-purpose tools. Batch production procedures are often associated with "job shops," which may vary in size from a two-man machine shop to companies like the Rohr Corporation in Chula Vista, California, which produces 8,000 to 15,000 different products and has an inventory of some 30,000 different items at any one time.

According to a respected Commerce Department economist, batch production techniques account for about 75 percent of U.S. production of discrete engineered products, by value. In considering that estimate, it is important to realize that although the final assembly steps in the manufacture of a product might be performed using "flow-through" mass-production techniques, many of its parts and subassemblies are frequently most economically created by batch production.

In assessing the impact computers will have on manufacturing, two dominating facts emerge from the above discussion: (1) most U.S. manufacturing is performed by batch production techniques; (2) batch production requires sophisticated scheduling and control of productions facilities; and above all, it requires flexibility in the use of those facilities.

How will computers most affect the manufacturing process? By bringing to the important area of batch production and job shop operations precisely those features most needed: flexibility in scheduling and control of resources, including control of the actual production processes themselves. Before considering the individual processes used in manufacturing and what computer

control has done and will do to them, a more basic question should be addressed: why introduce more computerization and automation into manufacturing?

Why Computerize Manufacturing?

There are several compelling reasons why the manufacturing process will continue to become automated, and why computers will become more and more directly involved in controlling all aspects of manufacture. Computerized automation will continue until people only supervise the process, provide middle- and high-level management decisions, and provide such services as acting as an interface to other people in sales or in creative design to meet aesthetic judgments and requirements. Some of the most important reasons for increased computerization of manufacturing are the following:

Reduced Prices. Computerized automation can dramatically reduce manufacturing costs, especially in a job shop environment. One indication is afforded by numerically controlled (NC) machine tools, and more recently by direct numerical control (DNC), linking the tool directly to a central computer, and computer numerical control (CNC), using a local minicomputer as controller; direct labor cost reductions of 75 percent over manually operated machine tools are routinely reported, with manufacturing times simultaneously reduced by 75 percent. The repeatability and uniformity of NC processing also reduces wastage and rejects. Huge job shop operations like the Rohr Corporation have installed computer-based inventory and warehousing systems to reduce costs. These examples are only an indication of the potential, because many manufacturing processes -- notably assembly -- are not yet under computer control.

The importance of reducing manufacturing costs, of course, goes beyond aiding the individual consumer. As the entire world increasingly becomes one marketplace and such nations as Japan compete directly with the United States in high technology products, our prices must remain competitive. Japan is, in

fact, heavily committed to computer-based industrial automation: a $100 million government-sponsored R&D effort is currently under way there in applied pattern recognition and robotics with the explicitly stated goal of industrial automation. The fruits of that program are already being seen. Japanese research results on robots with tactile sensors, reported at the recent Second International Symposium on Industrial Robots, surpass any U.S. efforts on tactile sensing. Our direct competitors will be reducing manufacturing costs through computer-based automation; with our labor costs much greater than theirs, flexible automation of high-technology manufacturing is probably the most important response the United States can make to remain in the international trading community.

Increased Product Quality and Uniformity. Most rejects and errors during a manufacturing process can be traced to human variability or error. By contrast, the use of numerically controlled machine tools for metal cutting provides an example of the reliability and effectiveness of machines in manufacturing. The manufacture of such products as precision waveguide slotted antennae or diffraction gratings requires the uniformity and reliability of automation. Increased use of sensors for closed-loop feedback will make machines more responsive to their environment and will lessen the occurrence of "dumb" errors which are sometimes associated with automation. But as humans intervene less and less in the actual routine manufacturing process, there will also be fewer "random" error conditions (caused by humans) with which machines must cope. Increased product quality will also result from the ability to schedule more thorough, uniform inspection steps during manufacture.

Customization of Products. One of the main themes of this article is that computers will bring a flexibility to automated manufacturing while maintaining a high productivity rate. The first manufacturer that can offer truly customized products (such as clothing to fit your precise measurements, perhaps with your own design modifications incorporated) at mass production prices will unleash a consumer demand that will cause the computer-based automation of entire industries.

Increased Job Satisfaction. The demeaning nature of many factory jobs is rapidly becoming a major labor issue. The current generation of workers is more educated and has more options available; they will not act like machines 40 hours/week. Fortunately, computer-based automation requires human labor, but in more satisfying jobs. The predominant factory jobs in the future will be programming, system maintenance, supervision and management.

Programmable Automation

The question is: On what time scale will computer-based automation of manufacturing proceed, and what form will it take? I am currently involved in an investigation for the Advanced Research Projects Agency (ARPA) of DOD which is formulating an answer to that question and to related questions of direct interest to DOD: (1) What will be the impact of computer-based automation on DOD procurement? (2) If there are significant benefits, such as reduced prices and shorter lead times, what technological developments are required to achieve computer-based automation so that those benefits can be realized?

There are, of course, no general answers; they depend on many characteristics of the product and on the manufacturing method. Our study has concentrated on the important job shop/batch production environment, and has formulated a concept of programmable automation for that environment. There are three key attributes distinguishing programmable automation of manufacturing; all components of the manufacturing process -- parts forming and machining, assembly, inspection, resource transfer and storage, and scheduling -- are:

(1) highly automated with human supervision, but requiring little human intervention in the routine manufacturing process (and therefore not limited by human reaction times or by human variability);

(2) flexible; all manufacturing components are programmable;

(3) highly integrated with computer-aided design and engineering facilities, accounting systems, and management information and manufacturing control systems, so that information acquisition from each of these areas contributes to the entire system.

Is complete programmable automation feasible today in a manufacturing facility? Probably not. But it is potentially closer than might be thought. To see how such a facility would operate and what developments are required for its realization, consider the following description of a "hardware realization" of the concept. (There are certainly other possible hardware realizations. The point is not how the concept is implemented, but rather that the entire manufacturing process be studied as a unified system.)

A programmable automated manufacturing facility is deceptively easy to imagine. The "plant floor" might consist of a number of work stations, distributed in a convenient manner (perhaps grouped according to function -- part forming and machining, assembly, inspection, storage -- for ease of maintenance, cleanliness requirements, etc.). Each work station performs a manufacturing operation under direct computer control, and is serviced by a computer-controlled "random-access" conveying mechanism. Such a conveying mechanism would be capable of transporting in-process materials between any two work stations in the facility, most probably on standard-sized pallets, under program control; this conveying mechanism would have the important property that it maintains control of the orientation of any palletized materials being transported. Actual implementation of the conveyor system might be in the form of a two-dimensional overhead grid of rails with turning points at some or all intersections and rail-mounted "part movers" capable of traversing the network, or it might use a number of floor-mounted carts capable of following buried cables. The interface between the conveying system (which would have limited degrees of freedom and coarse positional accuracy) and a work station (perhaps requiring rather

precise orientation and positioning of tools and in-process materials) might well be handled by an industrial robot with some limited sensory feedback capabilities. One robot would normally provide the I/O interface for a group of several work stations, since the processing time at a work station tends to be long relative to the I/O time.

From the foregoing cursory description of aspects of a computer-controlled automated manufacturing facility, some important attributes of that facility may be derived. First of all, it is flexible in several respects. Since the order in which manufacturing operations are performed is governed only by control of the conveying mechanism, rather than by physical placement of work stations in a "flow through" line linked by rigid conveyors, that order can easily be changed, e.g., to add additional inspection steps, or to incorporate a new manufacturing technique. In fact, such flexibility allows the manufacturing process to be quite adaptable to changes in materials and production technology; work stations incorporating a new technology can be installed in any spare location and "debugged," then introduced into the manufacturing process by modifying the conveyor scheduling algorithm to route in-process materials through that station.

Another form of flexibility involves efficient allocation of resources. If work stations performing assembly and inspection operations are programmable in the same manner that NC machine tools are, and if they are under direct computer control, then the most efficient use of the manufacturing facilities would probably encourage the manufacture of several different products concurrently using common manufacturing resources. By analogy, time-sharing a computing facility between several programs permits better use of resources, for example while awaiting completion of an I/O operation, than does the sequential execution of those programs (dependent, of course, on the required time to switch between programs; "switching" an assembly machine between different products may involve significant delays in exchange of work-holding fixtures, etc. Those delays must be taken into account.) Job shops today use

their facilities in a "time-shared" manner, but the lack of a complete, centralized cognizance of the status of all resources does not permit precision in scheduling the use of those resources. An often-quoted statistic in many current manufacturing operations is that an in-process part or subassembly sits idle, queued for the next operation, 90 percent of the time. The problem is one of management, and computers are well-suited to performing the rather low-level management decisions involved in routine allocation of resources, subject to human supervisory control and establishment of priorities.

The flexibility of a programmable automated manufacturing facility is naturally limited by the manufacturing processes implemented within it. (But not necessarily limited to one "plant"; nothing prohibits portions of the conveying network from involving transport between physically separate facilities, with a computer network maintaining control between the separate facilities.) It is also limited by size considerations. The most obvious implementation of a programmable automated facility would rely on several distinct standard-sized pallets for material transport, inventory, machine loading, etc. The pallet sizes become limiting factors. One facility will not produce both wristwatches and air compressors, but the concept of programmable automation can be applied to manufacturing facilities of considerably different scale.

Developments Required

Programmable automation is a prediction of how a manufacturing facility will operate at some time in the future. The concept provides a useful framework within which to evaluate steps currently being taken toward computer-based automation. Three examples of such steps are: numerical control of machine tools; industrial robots; and automated warehousing systems. Are current developments in these areas consistent with the overall concept of programmable automation described above?

Numerically controlled machine tools. There are three major areas of activity here. One involves DNC and CNC -- how to distribute the computing power between a centralized computer and an on-site minicomputer. The argument does not functionally change the characteristics of computer control of machine tools. More important is that machine tools be capable of communicating with a centralized computer-based control system; both DNC and CNC permit this.

A second area of activity is the trend toward a cluster of different machine tools (e.g., boring, milling, grinding) interconnected by a conveying system, with automatic loading and unloading of in-process materials from the individual machine tools. These systems permit a sequence of several different machining operations to be performed on a palletized part, under computer control, and without human intervention. Notable examples are Cincinnati Milacron's prototype Variable-Mission system and System 24 of Molins Machine Company, Inc. These systems incorporate the programmable automation concept to a considerable extent for the metal-removal component of the manufacturing process.

The third area of activity involves adaptive feedback and in-process inspection -- the use of sensors to monitor and control the machining process as it is being performed. Some increases in productivity will result from such adaptive control, but perhaps of greater importance to a highly automated facility is the ability of these sensors to detect such exceptional conditions as tool breakage.

In summary, the current state-of-the-art in the metal removal aspect of manufacturing is entirely consistent with programmable automation and, in fact, provides an example of such a system in microcosm.

Industrial robots. The current generation of industrial robots, exemplified by the Unimate (Unimation, Inc. Danbury, Connecticut) and Versatran (AMF Versatran, New Rochelle, N.Y.), are programmable "put and take" transfer mechanisms. They have no built-in feedback from tactile or visual sensors,

and rely on absolute positional accuracy (about .050" in a working area having a diameter of about 20 feet).

In a paper presented at the recent Second International Symposium on Industrial Robots, Mr. J. F. Engelberger, President of Unimation, Inc., states that second-generation Unimates will have a compatible computer interface, program memories of any desired size with random program selection, and the ability to synchronize with a moving target. He also predicts that a third-generation industrial robot, a "thinking robot with coordinated hand and eye won't be needed at all in the industrial environment. Basically, I agree with this prognosis, although there is really a spectrum of visual processing and coordination to be considered. Robots will retain their niche as a flexible interface between work stations and the conveying mechanism; this does not require complex visual processing or "intelligence." However, some degree of sensing and feedback -- especially tactile sensing -- is clearly desirable to reduce the precision with which known parts must be presented to these robots. In current applications, the cost of special tooling to retain precise part orientation for a robot application is often greater than the cost of the robot itself; limited sensory feedback would dramatically reduce the requirement for such special tooling.

Automated warehousing systems. This technology is advanced to the point of being ready for integration into a programmable manufacturing facility. Most such warehousing systems rely on standardized pallets, and are capable of being interfaced to a computer-based inventory control system.

Given the above inroads of computers into manufacturing, it may seem that computer integrated manufacturing systems are well advanced. Actually, there are major blockages to be overcome, especially in the following areas: (1) product design for automated assembly. Current design philosophies are too heavily biased toward the unique assembly capabilities of two-handed humans with their sophisticated visual, tactile, and force sensing systems; (2) programming of such processes as assembly and inspection; (3) a work

station specializing in visual processing, to perform subtle inspections, to provide initial orientation of parts, etc; (4) programmable assembly and inspection machines; (5) an integrated software system capable of data collection, resource allocation, scheduling, control of production processes, and interface to accounting and management systems.

The last two development areas in the preceding list are of special importance.

The assembly process typically accounts for about 35 percent of production cost for discrete engineered products. Especially in job shop operations, assembly is very labor-intensive. Consequently, it is subject to human variability and is not amenable to computerized coordination with other manufacturing operations. Therefore, programmable automated assembly machines are a vital component of an integrated manufacturing system. There are many tradeoffs to be investigated in automated assembly: (1) a group of inexpensive, rather specialized assembly devices vs. a sophisticated, more flexible machine; (2) rigidity and mass for absolute positional accuracy (in the manner of current machine tools) vs. flexible manipulators using sensory feedback for incremental accuracy (in the manner of human assembly workers); (3) the use of a general-purpose "wrist" capable of accepting special-purpose grippers and tools vs. a general-purpose "hand" which obviates the need for a collection of specialized grippers; (4) the use of two or three "hands" working in concert vs. one hand supplemented by work-holding fixtures and pallets. Most likely there is no single set of right answers. Initially, more data is needed on the nature of the assembly task so that the spectrum of possibilities is more clearly understood. However, our initial studies indicate that sophisticated visual systems and "artificial intelligence" are not needed for most assembly operations; the emphasis in development should be on simple vision devices and on low-bandwidth tactile and force sensing feedback.

The development of complete software systems for manufacturing facilities is, of course, crucial to the concept of programmable automation. Probably the largest development effort in discrete production control systems is being made by IBM. According to a recent Quantum Science Corporation market study entitled Factory Automation, IBM has captured 60 percent of the market for factory data collection systems. An 8-volume IBM planning document contains detailed specifications for a Communications Oriented Production Information and Control System (COPICS) governing almost all aspects of the manufacturing process (see Fig. 1): perhaps the single most important development in programmable automation would be the implementation and distribution of that system. The resulting de facto standardization of interfaces would bring to the area of manufacturing automation the same type of umbrella that has been in operation in the areas of computer peripherals and memory systems. Without such standardization, developments and products tend to become fragmented. (The only other alternative would seem to be an active role by such institutions as the National Bureau of Standards or the American National Standards Institute in setting interface standards for the modules of an automated production facility.)

The software system governing an automated factory will be large and complex; however, the system appears (from the COPICS specifications) to be highly modular, which will aid in its development. Such a system seems within the state-of-the-art in large software development efforts. It is important to realize, however, that the computer-software system must be used, and defined, directly by high-level manufacturing professionals, who may never have used computers before. Computer scientists will not be running the factory.

How Do We Get There from Here?

Naturally, there will not be a sudden quantum jump in the computer-based automation of present manufacturing facilities. Neither will large numbers of shiny new factories be built soon incorporating all of these concepts.

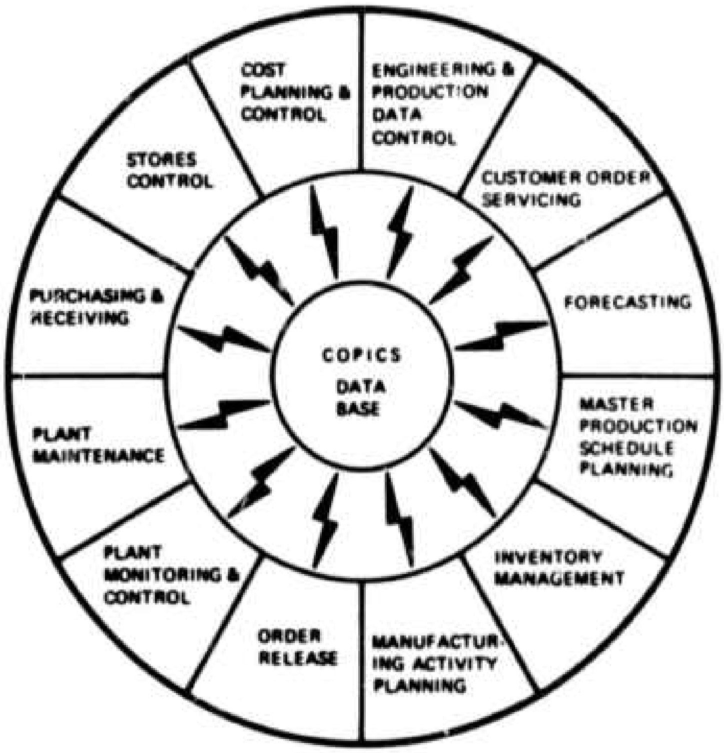

Fig. 1: Application Areas Covered by IBM's Proposed COPICS System

Courtesy of International Business Machines Corporation

The capital investment in current production facilities requires an evolutionary approach to their modernization.

It is quite possible for programmable automation to evolve in existing production systems. Initially, the individual work stations may rely heavily on human intervention, with the worker gradually assuming more of a supervisory role as the capabilities of the machine improve. Also, the conveying system may gradually expand from an initial automated warehouse to provide materiel routing among increasing numbers of work stations. However, for there to be an orderly evolution toward programmable automation, it is vital that an entire manufacturing facility be studied as a system; within that system, functional blocks must be identified and the interfaces between these blocks clearly delineated. Two obvious sources of interface specifications are the characteristics of the conveying mechanism -- which interfaces with nearly all other mechanical functions -- and of the information flow to and from the computer-based control system. During this evolution, it is important to work toward achieving the goal of total automation of the routine manufacturing operations. The maximum impact of computers in manufacturing will come from complete, real-time computer cognizance and control of all processes and resources, allowing the precise scheduling and allocation of those resources.

A prototype discrete manufacturing facility incorporating most of the concepts discussed in this paper could most probably be built before 1980 -- the difficulty of the task depending, of course, on the flexibility and programmability of the production processes and on the magnitude of the R&D effort undertaken. But the spread of computer-based automation into a significant segment of industry will take decades. (Numerically controlled machine tools were commercially available in 1955; at present -- eighteen years later -- less than one percent of the metal cutting machine tools in use are numerically controlled.)

It is becoming clear that a focused five- to seven-year development program aimed at total, integrated, computer-based automation of discrete product

manufacture can produce systems which will dramatically increase U.S. manufacturing productivity and increase the quality of both jobs and products. The emphasis in this program should be on developing flexible automation for assembly operations and on direct computer scheduling and control of all in-process materials and manufacturing processes.

The infusion of information sciences into the manufacture of discrete products requires a coordinated effort among government, universities, research institutes, and industry, with a recognized national priority. Computers will have a dominant role in future manufacturing technology. The benefits obtainable from their use are needed now.

GLOSSARY

Batch Production	Manufacturing facilities are used to produce a batch of identical or very similar products, then reconfigured for production of a batch run of a different product; the batch (or lot) size may vary from one item to thousands of items.
CNC (Computer Numerical Control)	Control of an NC machine by a local digital computer; in most cases the local computer will have a communication link to a larger, more centralized computer facility.
DNC (Direct Numerical Control)	Control of an NC machine by a remote digital computer.
"Hard" Automation	Special-purpose manufacturing equipment designed for the manufacture of a particular product; equipment requires substantial modification for re-use for another purpose.
Industrial Robot	A programmable material transfer device for use in factory environments.
Job Shop	A manufacturing facility which contracts to produce a specified quantity of a product; most often a number of different products are produced concurrently using some manufacturing resources in common.
Mass Production	Characterized by a high rate of production of identical or very similar products; transfer of in-process materials between work stations is usually automated.
NC (Numerical Control)	The actions of a machine are governed by specifications read from a tape, stored in a local memory device, or received over a communication link.
Process Industry	Creation of a bulk product by control of a continuous process.
Programmable Automation	All components of the manufacturing process are highly automated, programmable, and integrated with other relevant information systems.

GLOSSARY (Continued)

Tactile Sensing	The use of sensors to provide feedback similar to the sense of touch in humans.
Work Station	A location at which a step in the manufacture of a product is performed.

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